Fermilab FERMILAB-Conf-01/187-E July 2001

THE FERMILAB RECYCLER RING

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Abstract

The Fermilab Recycler is a permanent magnet storage ring for the accumulation of antiprotons from the Antiproton Source, and the recovery and cooling of the antiprotons remaining at the end of a Tevatron store. It is an integral part of the Fermilab III luminosity upgrade. The following paper describes the design features, operational and commissioning status of the Recycler Ring.

1 INTRODUCTION

The Recycler is a permanent magnet fixed energy storage ring. It is located in the Main Injector tunnel, directly above the Main Injector. Its circumference is 3319.4 m, the designed transition gamma is 20.4, and it operates at 8 GeV kinetic energy, well below transition. It has a designed transverse admittance of 40π-mm-mrad for antiproton transfer, and a momentum aperture of $\pm$0.25%.

2 OPERATIONAL GOALS

The main purpose of the recycler is to augment the luminosity improvement through injecting more antiprotons into each Tevatron store. First, the recycler can help maintain an optimal stacking rate in the accumulator by receiving periodic antiproton transfers from the accumulator, as a large stack size in the accumulator causes the stacking rate to decrease. Secondly, the recycler can receive antiprotons from the Tevatron at the end of a store, re-cool the antiprotons, and re-inject the antiprotons back into the Tevatron.

In the first scenario, antiprotons do not undergo energy changes, and the transfer can in principle be made via a dedicated beamline between the accumulator and the recycler. Currently this operation is made via the Main Injector. The recycling of antiprotons from the Tevatron, however, requires deceleration and acceleration RF gymnastics, which will be performed in the Main Injector. The description of the Main Injector RF manipulations can be found in [1]. The recycler is designed to store different types of antiproton beam in various state of cooling through the use of a barrier bucket RF system [2] which will be described briefly in the following section.

For the Recycler to fulfill its Run IIa roles, it has to meet the following performance goals:

- 100% efficiency for antiproton transfer
- Beam lifetime of 10 to 30 hours without cooling and 30 to 100 hours with cooling
- Store 2×10^{12} antiprotons

3 COMPONENTS

The following is a list of major technical components in the Recycler.

3.1 Magnets

Both permanent magnets and powered correctors are employed in the commissioning of the Recycler.

3.1.1 Permanent Magnets

The recycler permanent magnets include 344 gradient magnets, 92 quadrupole magnets, 5 Lambertsons, mirror magnets and transfer line dipoles. These are made of type 8 strontium ferrite for low cost, temperature stability and radiation resistance. The temperature coefficient of the ferrite material is corrected by interspersing an iron-nickel alloy with a low Curie temperature between the ferrite bricks above and below the pole tips. Test showed that over the range of $37\pm7^{\circ}C$ (far greater variation than would be expected in the tunnel) the maximum deviation was 1×10^{-4}. A test magnet was irradiated with 0.3 Mrad/hour for about 100 Mrads with a change of about 3 parts in 10,000, which is within allowed variation. In addition, tests were performed regarding mechanical shocks and demagnetization due to Main Injector stray fields; no significant effects were found. Field strength versus time tests corresponded to a change of less than 0.05% over a 20 year span.

3.1.2 Powered Correctors

Powered correctors in the Recycler ring include 81 dipoles, 20 quadrupoles, 24 sextupoles and 4 skew quadrupoles. Tunes can be adjusted without altering the ring wide lattice using a Phase Trombone [3] in the 60 sector.

3.2 RF System

The Recycler RF system consists of four 50 Ω ferrite loaded cavities each driven by a 3.5 kW wide-band (10kHz – 100 MHz) amplifier. The system is capable of generating 2.5 MHz, 7.5 MHz and barrier bucket wave forms. The barrier buckets are two rectangular pulses which capture a bunch of beam (Fig. 1). Feedback loop corrections are provided for square pulse voltage droop, baseline offset and beam loading problems. The Recycler in its final operational mode can contain 4 barrier buckets along its circumference at a given moment.

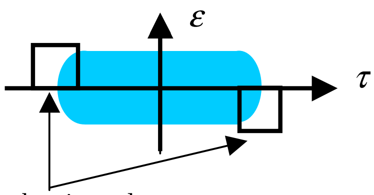

Figure 1: Barrier bucket RF system. Particles with positive energy errors slip to the right and are decelerated by the negative RF pulse; those with negative energy errors are accelerated by the positive pulse.

3.3 Vacuum System

The Recycler beam pipe is 1.75” by 3.75” (ID) stainless steel except in the MI-60 Phase Trombone section where 3” OD round pipe is used for additional vertical aperture. All pipes, BPM tubes, titanium sublimation pumps (TSP’s) and shielded bellows underwent a hydrogen degas process described in [1] to achieve low outgassing rates. For the 104 cells in the Recycler ring, there are one ion pump and 5 TSP’s per cell, and 26 manual sector vacuum valves for the whole ring. In addition, ion clearing electrodes are provided for antiproton operations. The average pressure in the ring is a fraction of a nano-torr.

3.4 Stochastic Cooling

The Recycler employs both stochastic (present) and electron cooling (2003). This section will be devoted to the stochastic cooling system only. For momentum cooling with a beam of $\pm$0.25% momentum spread the Recycler employs two filter cooling systems (0.5 – 1.0 GHz and 1.0 – 2.0 GHz) which require no Schottky band overlapping. The transverse betatron cooling systems are limited to a maximum frequency due to the “bad mixing” between pickup and kicker; for the specified momentum spread the cooling bandwidth of 2.0 – 4.0 GHz is chosen. The cooling signal is transmitted with a modulated laser signal across the ring for the corresponding arc 1/6 of the circumference.

A cooling test was made using the proton beam and a proton cooling tank during October 2000 with a result of increasing the beam lifetime by a factor of two.

3.5 Diagnostic Instrumentation

A more detailed account of the Recycler diagnostics can be found in [4] in these preceedings. In this section only the BPM system, transverse Schottky detectors and Ion Profile Monitors will be discussed.

The Recycler Beam Position Monitor (BPM) system is of the split tube type located at the 1/3 and 2/3 boundaries of each half cell totalling 416 detectors per plane. This provides 8 detectors per betatron wavelength. The system measures orbit of the injected beam from the Main injector, and closed orbit of the circulating beam. An application has been created with which turn-by-turn analysis can be made [5]. There is some coupling between the two plates in the circuit formed by the plates and the pre-amplifier in the tunnel, which makes trigger timing and calibration of the system rather critical for stable performance.

The Recycler transverse Schottky detectors are the stainless steel split tube type 1 meter long and 7 centimeter in diameter resonated at 238.5 times the revolution frequency. The current system has adequate signal-to-noise ratio for a large proton beam. For the anticipated small cooled antiproton beam a more sensitive system is necessary and an upgrade is being planned.

The Ion profile Monitors (IPM’s) in the Recycler is similar to those described in [6]. The IPM system is capable of capturing the beam profile on a turn-by-turn basis providing information including beam centroid position and fitted sigma.

Other diagnostic tools include a Beam Loss Monitoring (BLM) system shared with the Main Injector; wide band pickups for general purposes, Direct Current transformer (DCCT) for stored beam current monitoring, and toroids for turn-by-turn beam current monitoring.

4. Commissioning Status

4.1 Improvements and Upgrades

Many improvements have been made to the Recycler since its commissioning two years ago. These include:

- BPM system upgrade to 7.5 MHz resonance circuit for stable operation
- Gradient magnet end shims replacement to address sextupole feedown effect
- Realignment of magnets, beampipes and BPM’s
- Improved vacuum to 1×10^{-10} torr

- Magnet moves to reduce closed orbit oscillation
- Improved magnetic shielding
- Installing skew quadrupoles in the RR-32 line to remove skew quadrupole effects measured in the injection Lambertsons.

For the near future the following upgrades are planned:

- Complete the magnet realignment
- New transverse Schottkies for more sensitivity
- New longitudinal Schottky detector
- Mechanical scrapers for calibration purposes
- More software tools for analyses
- Additional correctors

4.2 Commissioning Status

So far the recycler commissioning has been performed using reversely injected protons through the RR-32 antiproton extraction line, with the exception of a test in which antiprotons were injected successfully into the Recycler.

The efficiency of the RR-32 transfer line has been near 100% without turning on the powered correctors, but these are necessary for properly matching the injection position and angle of the beam to the Recycler.

The injection efficiency of the proton beam in the Recycler has been near 100% as measured by the two toroids, one near the downstream end of the Lambertson (TOR330) and the other at about 5/6 of a full turn (TOR213). Turn-by-turn toroid data showed that a fast loss occurs in the first ten turns or so of about 10%. For the stored beam, a circulating efficiency of about 90% has been achieved based on the Recycler and Mian Injector DCCT ratio (Fig. 2). Analyses based on BPM and IPM data for turn-by-turn orbit oscillation and emittance growth is being performed to improve the performance.

The beam loss pattern over time (~1 hour) is steeper than an exponential, therefore a forced exponential fit over different time segments yielded different lifetime values. For a horizontally and vertically scraped beam, for instance, a fitted exponential for the first 15 minutes has a slope of over 20 hours if the Main Injector is not ramping. As seen in Fig. 3, once the emittances (R:EMITHN and R:EMITVN) reach the aperture limit beam loss reaches an equilibrium for a lifetime of 3 to 4 hours.

5 SUMMARY

The Recycler performance has improved significantly over the past year. For an injected beam of 10π-mm-mrad the circulation efficiency is over 90%. It has been demonstrated that stochastic cooling of a proton beam was effective in a 100% increase of lifetime, and currently the initial lifetime of a scraped beam is over 20 hours before the beamsize approaches the aperture limit. The upgrades planned for this September shutdown will further improve the performance of the Recycler.

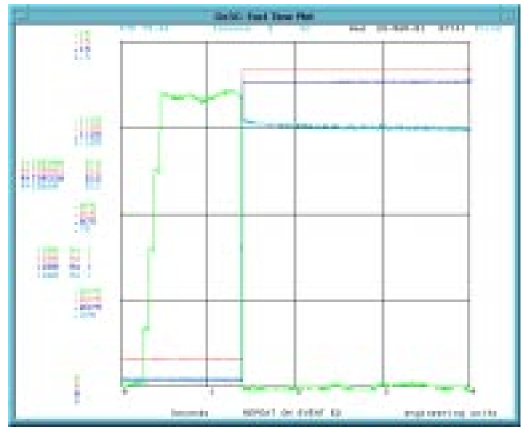

Fig. 2: Injection and circulating efficiency

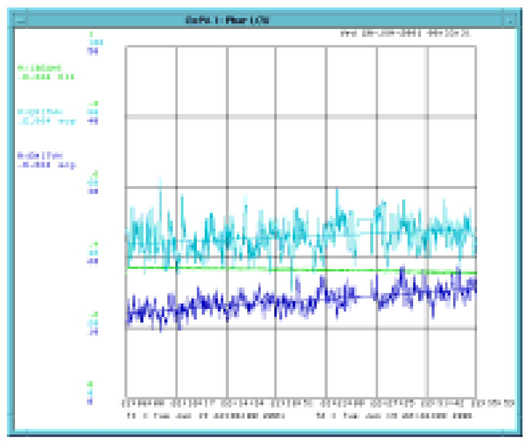

Fig. 3: Beam lifetime and relative emittances

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